5. SUPERCONDUCTING MAGNETS

The past year has been a turning point in the Superconducting Magnet Program, with a number of milestones reached in both the magnet fabrication and materials development aspects of our mission. The hybrid niobium-titanium/niobium-tin dipole magnet, D19H, was completed and tested in August 1996. Fabrication and assembly work on the 4-layer Nb_3Sn dipole magnet, D20, was completed in November 1996, and the magnet is presently being tested. At present, we have reached a new record field for a dipole magnet of 13.5 tesla using D20; the test results are described later in this chapter.

Several new magnet designs are being studied in detail. Three alternative interaction region quadrupole designs, based on Nb_3Sn, are being analyzed—a block, a pipe, and a more conventional cosine 2θ geometry. Several block-geometry dipole designs are also being analyzed; these include designs proposed by others (McIntyre of Texas A&M University and Gupta of Brookhaven National Laboratory) as well as our own. In addition, we have been participating in the muon collider design effort (see Chapter 3) and have proposed magnet designs for several key components, including the interaction region quadrupoles.

In superconductor wire and cable development, a program has begun for testing new conductors in the form of coils inserted into the bore of D19H and/or D20. The first test coil, made from a "bronze process" Nb_3Sn cable in collaboration with KEK, will be tested in D20 as soon as the initial testing of D20 is completed in March 1997. As part of our continuing search for new superconductors usable in accelerator magnets, we have procured samples of Nb_3Al and Bi-2212 in the form of round wire. These conductors are being evaluated and procedures are being developed to fabricate multi-kiloampere conductors. Development of artificial-pinning-center Nb_3Sn is also proceeding; highlights include the development of a rapid screening program based on thin film semiconductor processing, as described in more detail later. Our work on understanding and controlling interstrand resistance, in collaboration with Collings' group at Ohio State University has been expanded to include Nb_3Sn, Nb_3Al, and Bi-2212 materials as well as the NbTi cables evaluated previously.

The design and fabrication of dipole and quadrupole magnets from ductile superconductors such as NbTi is a mature technology. Although we continue to maintain our expertise in this area, most of our emphasis on new materials and magnet design is now focused on brittle materials and the development of magnet technology for these materials. One way we maintain our existing ductile-materials and magnet expertise is through our participation in the U.S. Large Hadron Collider collaboration. This work includes development of high aspect ratio cables (for the LHC interaction-region quadrupoles) and cabling technology for the LHC dipole magnets. In addition, we are continuing to provide magnets for closely related programs such as the ALS Superbend investigation and the Electron Cyclotron Resonance ion source magnets for nuclear physics, which have been supported with Laboratory-Directed Research and Development (LDRD) funds.

Our work on cosine 2θ magnets will be focused on a high gradient quadrupole which can be used as an upgrade for the interaction regions of the LHC and/or the Tevatron. This work will be done in collaboration with Prof. L. Rossi's group at LASA in Milan. Prof. Rossi has support for this work from the Italian Government through INFN, and has completed a conceptual design of a high gradient quadrupole similar to what we have been studying. By combining our efforts, we can make more rapid progress; in addition, Prof. Rossi will work with an Italian company, EM-LMI, to procure part of the superconductor required for this project. The prototype magnets will be built and tested at Berkeley Lab. The design and some fabrication work will be completed in FY 97, and the magnet will be tested in FY 98.

The performance of D19H and D20 successfully demonstrated a number of key technologies necessary for the use of brittle superconductors such as Nb_3Sn. However, the results also pointed out the difficulties of extending the technology of cosine θ magnets to fields much higher than 13 T. There is a certain range of allowable coil pre-stress; its minimum is the pre-stress required to prevent the pole turns from delaminating, and its maximum is determined by the peak midplane stress developed at maximum field. In the cosine θ design, these stresses are additive at the coil midplanes. This conclusion leads us to look at different magnet geometries for higher fields.

Block coil designs provide the opportunity to apply the necessary coil pre-stress in such a way that the Lorentz force loads builds up in a more uniform manner in the coils. The first steps toward block coil designs are being taken in FY 97, with the construction of several insert coils for testing new conductors in the bore of D20. Insert coils of Nb_3Sn from a new manufacturer will be tested, as well as Nb_3Al and Bi 2212 high-temperature cable conductors. In addition, new insulating materials that are compatible with the higher reaction temperatures of Nb_3Al and Bi2212 will be tested. Cables of these new materials will be fabricated with cores so that the interstrand resistance values can be increased. This work will be done in collaboration with T. Collings' group at OSU.

We will continue the collaboration on high field block dipole design with P. McIntyre's group at TAMU. Specific tasks performed at LBNL will include the fabrication of cables for the TAMU model magnets, heat treatment of the Nb_3Sn coils, and magnet testing of the first model magnets.

Magnet R&D Highlights:
Dipole D20 Sets a New Record at 13.5 Tesla

On March 13, the 1-meter-long Nb_3Sn dipole magnet D20, designed and built at Berkeley Lab, reached a new record field of 13.3 tesla; not long thereafter it reached 13.5 T at 1.8 kelvins. These values much surpass the record set in June 1995 of 11.03 T for a similar type of 50 mm bore, 1 m long model dipole that was build by the Twente University Group and tested at CERN, as well as the previous record of 10.5 T at 1.8 K, which was set in NbTi model magnets being built for the Large Hadron Collider Project at CERN. These figures may be compared to the field strengths used in existing and planned superconducting accelerators: the Tevatron operates at about 4.5 T, HERA operates at 4.6 T, the LHC plans to operate at 8.6 T, and the SSC would have operated at 6.6 T.

The 10.5 T record was set with ductile NbTi superconductor, the stuff, in fact, of all practical superconducting accelerator magnets to date. The successful demonstration of higher field dipoles here and at U. Twente will provide the database necessary for accelerator designers to consider a new generation of higher energy colliders based on brittle materials like Nb_3Sn. But designing and fabricating magnets from brittle superconductors requires a major departure from the technology used for ductile materials.

Building and Testing D20

The Nb_3Sn superconductor composite can withstand only about 0.6% strain before permanent degradation in the superconducting current density is observed. The fabrication process used for D20 requires that the cable be wound into the magnet before the brittle Nb_3Sn compound is formed, and then the Nb_3Sn phase is obtained by heating the coils to 950 K for about ten days. The coils are then cooled to ambient temperature, assembled into the dipole magnet, and then cooled to 4.3 K. The strain state of the conductor must be calculated for each step of the process after the material is reacted and the strain must be kept below some low threshold, usually less than about 0.5%.

This is challenging, because from a reaction temperature of 970 K to a test temperature of 4.3 K, differential thermal contraction effects are large and can lead to unacceptably large strains. The thermal expansion (contraction) coefficients must be known for many components—iron yoke, stainless steel wire and shell, bronze shell and end pieces, superconducting cable, fiberglass/epoxy/impregnated coil structure, etc. In addition, the magnet fabrication procedures must be thoroughly developed so that the conductor is not strained in the critical steps after reaction and before the coils are epoxy impregnated. Finally, the magnet pre-stressing approach must be chosen carefully so that the coils are not damaged.

Leading up to the actual magnet construction, a series of component tests were completed in order to develop the database needed to perform the stress calculations and assembly operations for brittle conductors. These tests included:

- Composite coil thermal expansion coefficient and modulus of elasticity
- Differential thermal analysis of the composite superconductor wire and cable
- Critical current as a function of transverse strain
- Nb_3Sn to NbTi joint resistance as a function of field

In addition, a new assembly procedure was developed so that the pre-stress could be applied to the coils in a controllable and reversible manner. This procedure, involving a multiple layer wrap of stainless steel wire, has proven to be a simple and reliable method for achieving coil pre-stress.

D20 Training History

The magnet was ramped to a field slightly above 10 T before the first quench occurred on the top inner layer coil. The quench velocity was slow, about 10 m/s, which usually indicates that the magnet is far from the short sample critical current limit. The data were analyzed and everything looked normal—splice joint resistance, temperature rise in the coils, protection heater firing, etc. Further ramps were performed in order to see if the magnet could be trained up to higher fields (see Figure 5-1). The magnet trained up slowly but steadily, with only a few fallbacks to lower values, to a field of 11.14 T after 13 training quenches. Most of these training quenches were in the top inner coil on the pole turn. The location was estimated from the voltage tap and quench propagation information; these pole turn quenches were not stationary, but moved around during subsequent quenches. In addition, fast motion events were monitored during the current ramping and were indicative of motion-induced heating.

After the field was swept through a given region, subsequent sweeps showed a much smaller number of fast motion indications. These results suggest that the cause of the quenching may be the gradual delamination of the coils from the bronze pole pieces. This interface is rather weak compared to the fiberglass epoxy composite structure found within the coils and thus it would not be surprising to see delamination in this region if the coil precompression at the pole was reduced to zero. The pole strain gage readings for the layer one coil indicate the pre-stress on this coil is low and that the coil may be unloading at the pole during ramping. After the 11.14 T value was reached, the magnet failed to reach higher fields on the next 4 ramps.

After reviewing the data, it still appeared that the magnet was far from the short sample limit—the quench velocities were still low, and the quench position was moving around the pole. Also, since the quench locations were predictable, sensitive voltage vs. time data were obtained which allowed the "hot spot" temperature to be calculated from the copper resistance vs. time plots. These calculations indicated that the hot spot temperatures were quite acceptable—around 160 K. We felt that training should be pursued, but that further training at 4.3 K did not appear promising.

Consequently, we decided to try training at reduced temperature, although nobody expected to see a dramatic effect, since the temperature dependence of the Jc for Nb_3Sn is not so great as for NbTi, for a temperature decrease of only 2.4 K. However, we were wrong! The magnet was cooled to 2.1 K for the first training quench. This temperature was chosen so that the coil heater capability could be evaluated before going into superfluid helium, where their effectiveness might be reduced. The magnet reached 11.8 T before quenching, and the quench propagation heaters worked fine. The magnet was cooled to 1.8 k and the magnet reached 12.02 T before quenching. Training at 1.7-1.8 K was continued, and the quench point steadily climbed until a field of 13.3 T was reached on quench number 26. This quench occurred near the splice joint on the bottom outer coil. Training was continued for another three quenches, but the subsequent quenches all occurred at the same location and the quench current did not increase.

Next, we decided to warm the magnet to 4.3 K in order to see if the magnet training would be preserved at this temperature. The results here are not completely clear, since the extraction system was not activated and the magnet temperature reached upon quenching was higher than previously. The magnet showed some loss of training at 4.3 K, but did train back to the 12.8 T range in three attempts. Experiments are continuing to try to understand the training behavior and to find the operating limit at 4.3 K.

Figure 5-1. *The training history of D20 en route to a new record.*

Future work

The successful demonstration of this new technology for working with brittle materials is essential for progress in this field, since all practical superconductors with the exception of NbTi, are brittle. NbTi is limited to fields of about 10.5 T or less, so to reach higher fields Nb_3Sn presently the favored material. However, several new materials show promise, and we plan to use the D20 magnet as a test bed to explore the potential of these new materials, which include Nb_3Al and the high temperature superconductors based on Bismuth Strontium Calcium Copper Oxide (BSCCO). We will construct flat "racetrack" coils of these materials and test them in the high field bore of D20. We will then use these data to choose the most promising candidate materials for a new generation of high field dipoles beyond D20.

Reported by Ron Scanlan

Materials Research Highlights: A Novel Fabrication Method for Producing Engineered Microstructures in Superconducting Nb_3Sn Films

For many high magnetic field applications the critical current (I_C) of existing multifilamentary Nb_3Sn conductor must be increased or other processing methods and materials must be developed. The powder-in-tube technique for Nb_3Sn produces a very high critical current density (J_C) but it also produces large filaments (~50μm) and problems are encountered when fabricating long lengths. The oxide superconductors hold promise due to their high upper critical fields at low temperature. However, there are still many processing problems to overcome to produce affordable conductor with critical currents of practical interest. In the short term (about 5 years) Nb_3Sn will most likely be the only high field conductor produced in uniform long lengths. Therefore, one must find methods to increase its I_C.

This can be achieved by either increasing the amount of Nb_3Sn in a conductor's cross section or by improving the "quality" of the Nb_3Sn, with "quality" being improved microstructure or composition. Unfortunately, there are limits on the amount of Nb_3Sn that can be placed in a cross section of a wire, since a wire needs some Cu for thermal and electrical stability and some bronze to supply the tin for the Nb_3Sn formation. Therefore this technique can be expected to increase the critical current by a factor of two at most. Even if one could produce a wire with less Cu and bronze it would be less stable than present wire, resulting in magnets that are difficult to protect and wire that is more susceptible to degradation during cabling. Therefore, it seems that the most likely route to increase the critical current for "bronze-processed type" conductor is by improving the quality of the Nb_3Sn.

R&D Toward Better NB_3Sn

Prior work on Nb_3Sn has shown that grain boundaries provide flux pinning with smaller grains providing more pinning and thus higher critical currents. For a given "bronze" type process the grain size is determined by the temperature and time of the heat treatment, with the higher temperatures and longer times producing a larger average grain size. As in most materials, grain growth during heat treatment is a function of the thermodynamics of the system and the reduction in the total surface energy associated with the grain boundaries.

The success of the artificial pinning center (APC) approach to engineer the desired microstructure by design in Nb-Ti conductor and the theoretical prediction of very high J_C's for Nb_3Sn have sparked interest in APC or engineered microstructure (EM) approaches for Nb_3Sn. Extension of the EM approach to Nb_3Sn requires that a second phase be introduced into the Nb_3Sn reaction layer with the intent of increasing the volume pinning strength. This can be achieved either by the refinement of the Nb_3Sn grains due to the presence of a second phase, or by flux pinning that is caused during operation by the second phase itself. At least four criteria must be met for an element to be a candidate for the EM approach:

1. An element should not form intermetallic compounds with Nb. This would remove Nb_3Sn from the cross section and also cause fabrication problems when attempting to produce small Nb filaments. This leads to the second criterion.
2. An element should be co-deformable with Nb.
3. An element should not substitute for Nb or Sn in Nb_3Sn. This would alter the intrinsic properties of the Nb_3Sn, which could have a beneficial affect as with Ti or Ta , but this would remove the element from "engineering the microstructure" or pinning flux.
4. An element should be a strong oxide former or form intermetallic compounds with Cu or Sn. This would permit the formation of another phase within the Nb_3Sn layer during its formation producing the desired two phase engineered microstructure.

If one used a strict definition for APC , only the second pinning mechanism would be considered, but for this work the idea of APC is extended to include second phase additions that alter the microstructure and thus change the pinning force. One of the first applications of the APC approach was for Nb_3Sn tape conductor with ZrO_2 inclusions produced by internal oxidation of a Nb-1%Zr tape. The presence of these particles in the Nb tape inhibit grain growth during Nb_3Sn formation at high temperature.

Applying EM to a "Bronze-Type" Process

The first attempt at applying the EM approach to "bronze-type" processes was made by adding Ta and Cu as distinct phases to the Nb core. The results were inconclusive. It is not clear if the increase in J_C for the Ta EM material was due to an increase in the upper critical field from doping of the Nb_3Sn with Ta or from one of the EM mechanisms stated above. The critical current of Cu EM wires has yet to be measured. However, the material may have a small grain size and thus a higher critical current, since observations show that the reaction rate is significantly increased by the addition of Cu. For both of these additions it was difficult to obtain the large strains required to produce small filaments with a second phase uniformly distributed within them.

A schematic of a powder process approach that could be used to produce EM's is shown in Figure 5-2. This figure illustrates the large strains required (greater that 10^5) to produce very small fibers or ribbons in a Nb filament.

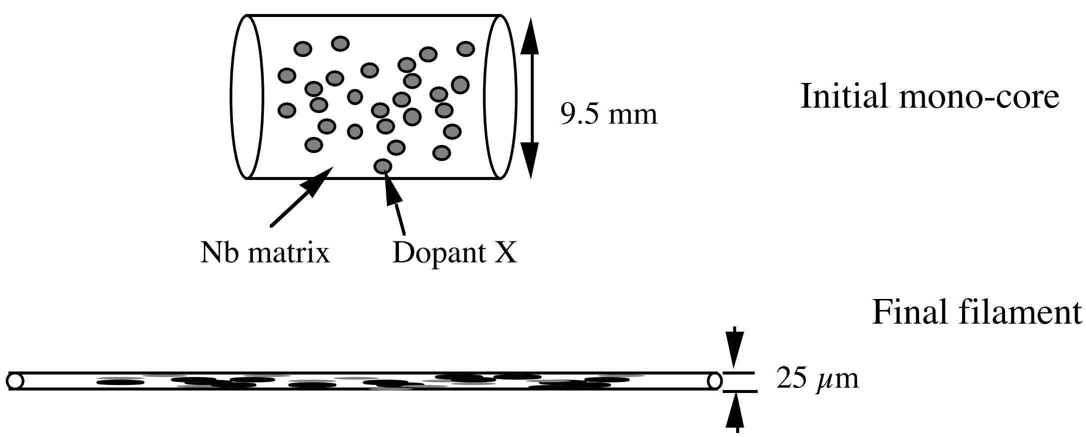

Figure 5-2. *Schematic of a powder process for artificially engineered microstructures in Nb_3Sn. Large strains (greater than 10^5) are needed to produce a fine distribution of fibers or ribbons in the Nb filament to an extent that lets them pin flux or inhibit Nb_3Sn grain growth during reaction.*

A Thin Film Approach to EMs

This work attempts to avoid the wire fabrication difficulties associated with multifilamentary wires by using thin film processing techniques. This permits one to separate fabrication issues from fundamental superconducting materials issues. Thin films of (Nb-X)-(Cu-Sn) are being produced by e-beam co-evaporation onto Si substrates with an SiO_2 buffer layer. Figure 2a shows a schematic of the as-deposited film in cross section. With the addition of certain elements, mostly rare earth elements, to the Nb film, one can produce a uniform dopant distribution with a small size prior to heat treatment. After heat treatment and patterning for I_C measurements one obtains the structures seen in Figures 5-3 and 5-4.

{ EMBED Word.Picture.6 }

Figure 5-3a. *Schematic of as-deposited films in cross section on (100) Si substrate with an SiO_2 buffer layer.*

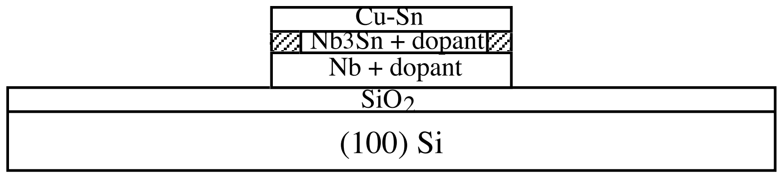

Figure 5-3b. *Schematic of the film in cross section after heat treatment and patterning with photolithography techniques to produce lines and pads for critical current measurements.*

The initial three elements chosen to add to the films were Y, La and Ti. The Y and La to were used test the EM approach, and Ti was used to increase the upper critical field (H_{c2}). Ultimate the films will be doped with at least two elements such as Y and Ti. One to alter the structure and the other to enhance H_{c2}. This is also necessary to determine if there are any Y and Ti interaction or compound formation.

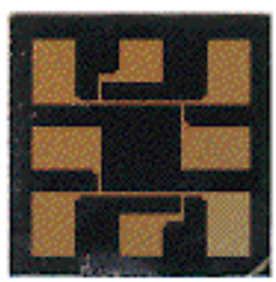

Figure 5-4. *A chip (15 x 15 mm^2) used to measure the critical current of Nb_3Sn/Cu-Sn films. The pattern was produced using standard photolithography techniques developed for semiconductor processing. Each chip has two lines 250 µm wide and a total Nb plus Nb_3Sn thickness of about 400-500 nm.*

Critical Current Results

The normalized critical current densities of films are shown in Figure 5-5. The film of Figure 5-5a is undoped while the films of Figures 5-5b and 5-5c are Y-doped and Ti-doped, respectively. Since the Nb_3Sn layer thickness is not known the critical currents densities ($J_{c,Nb}$) have been normalized to the initial Nb layer thickness (i.e. as deposited thickness). Another source of J_c variation between lines of the same film can be seen in Figure 5-6, where during photolithography a section of the line was removed. This would increase the critical current densities of the values reported here.

One can see that for the same heat treatment—700° C for 30 minutes—the Ti-doped film has the highest $J_{c, Nb}$ while the undoped film has the least. Both doped films have higher $J_{c, Nb}$'s; however, without more information about the Nb_3Sn layer thickness it is difficult to conclude that the dopants have altered the microstructure. When the undoped material is heat treated for one hour its critical current density increases to values similar to the Y-doped sample. This suggests that the Nb layers are not completely reacted. Longer heat treatment times must be examined. However, this could produce strong interactions between the substrate and the films since most of the dopants will reduce the SiO_2 buffer layer resulting in the formation of Nb silicides. Nevertheless, the $J_{c,Nb}$ of the Ti-doped film is about a factor of three larger than the undoped film at all fields. If the growth rate of the Nb_3Sn in the Ti-doped films is three times faster than the undoped films then most of the increase in $J_{c,Nb}$ can be accounted for. Since Nb will not carry any current at these fields the J_c of the Nb_3Sn layer must be very large.

The data also shows that the Ti-doped films have a smaller J_c vs. H slope than either the undoped or Y-doped films. This suggests that Ti may have substituted for Nb forming $(Nb,Ti)_3Sn$ which has a higher upper critical magnetic field. Ti doping effects are usually observe in fields above 12T The curves for the Y-doped and undoped films have about the same slope suggesting that Y does not affect H_{c2}. The films may also be in a tensile strain state due to a difference in the coefficient of thermal expansion of the Nb, Nb_3Sn and Si. This would depress J_c especially at higher fields. However, without higher field data or data for films on other substrates it is difficult to make strong conclusions.

Even though some work must still be done to decide conclusively if engineered microstructures can be produced in Nb_3Sn, a process has been developed to produce uniform films with interesting Jc's that merit further characterization. The process has also developed to a stage that the Nb film can now be doped with some of the other candidate elements.

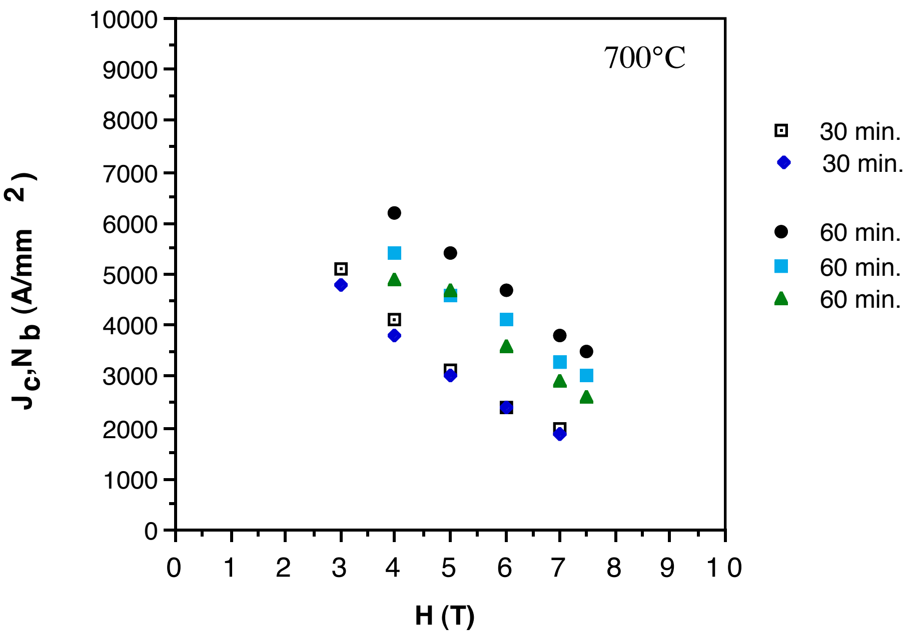

Figure 5-5a. *The critical current density of undoped films heat treated at 700°C for 30 and 60 minutes. The data has been normalized to its initial Nb layer thickness.*

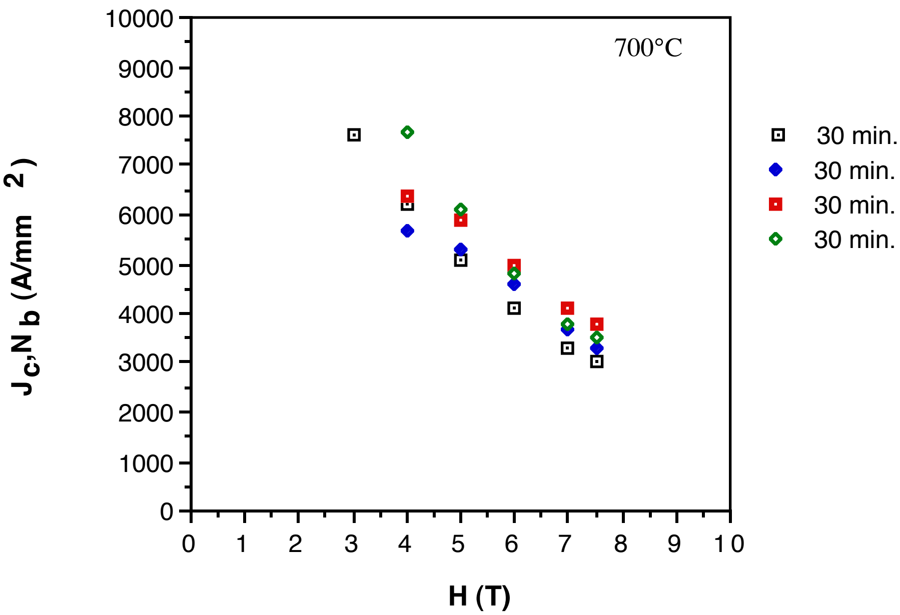

Figure 5-5b. *The critical current density vs. field of Y-doped films heat treated at 700°C for 30 minutes. The data has been normalized to its initial Nb layer thickness.*

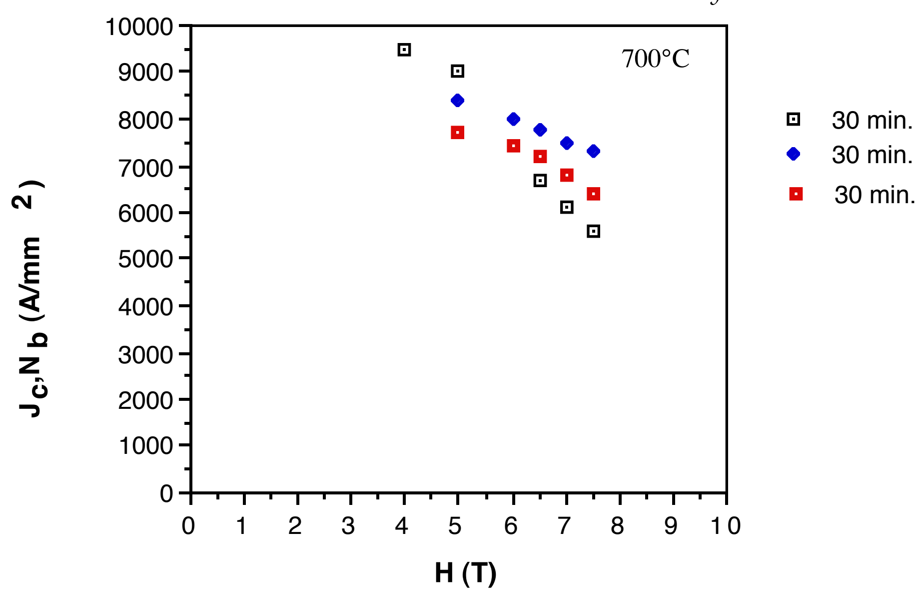

Figure 5-5c. *The critical current density vs. field of Ti-doped films heat treated at 700°C for 30 minutes. The data has been normalized to its initial Nb layer thickness.*

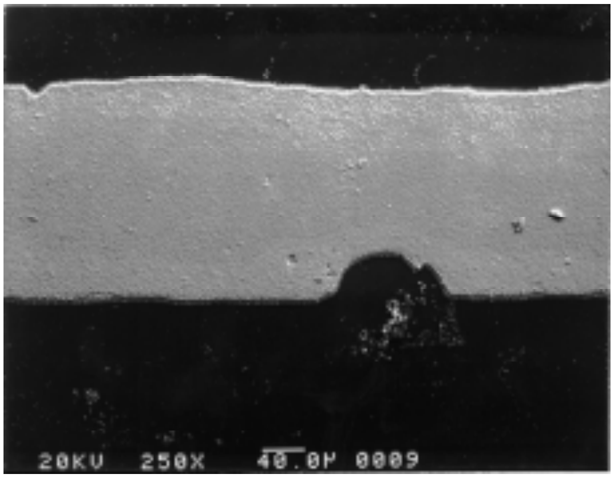

Figure 5-6. *Scanning electron microscope image of a line from an undoped film heat treated for 60 minutes at 700°C. Note the defect in the line that was introduced during photolithography.*

Reported by Daniel R. Dietderich